Renewable and Sustainable Energy Reviews 19 (2013) 37–51

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Technical and economic analysis of large-scale wind energy conversion systems in Algeria

S. Diaf [a,*], G. Notton [b]

[a] Centre de Développement des Energies Renouvelables, B.P. 62, 16340 Bouzareah, Algiers, Algeria
[b] Université de Corse CNRS, UMR 6134, Centre Scientifique de Vignola, Route des Sanguinaires, F-20000 Ajaccio, France

ARTICLE INFO

Article history:
Received 1 April 2012
Received in revised form
7 November 2012
Accepted 8 November 2012
Available online 5 December 2012

Keywords:
Wind energy
Weibull distribution
Power density
Capacity factor
Cost analysis

ABSTRACT

In this study, the wind energy potential and economic analysis in 13 locations are investigated using wind speed data measured at 10 m height. From the collected data which are the daily, monthly and frequency profiles of the wind speed at these sites, the southern region of Algeria is found to have the relatively highest wind potential. Technical and economic evaluations of electricity generation from different commercial wind turbines are examined. The yearly energy output, capacity factor and electrical energy cost of kWh produced by the selected wind turbines are calculated. In term of energy production, the results show that Adrar is the best location for harnessing the wind power and generating electricity. The capacity factors are found to vary from 6% at Skikda to 48% at Adrar. In addition, it was found that the minimum cost per kWh of electricity generated is about 0.0179 $/kWh at Adrar for the southern region, 0.0431 $/kWh at Oran for the coastal region and 0.0518 $/kWh at Setif for the highland region. Among all the considered models, the Suzlon S82–1500 wind turbine is found to be the most attractive in terms of cost per kWh. Based on the obtained results, the wind resource appears to be suitable for power production in the southern region, which makes it a viable substitute to diesel oil for electricity generation.

Contents

* Corresponding author. Tel.: +213 21 90 15 03; fax: +213 21 90 16 54.
E-mail addresses: sdiaf@hotmail.com (S. Diaf), gilles.notton@univ-corse.com (G. Notton).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.11.026

1. Introduction

Environmental pollution, caused by the use of fossil fuels in order to meet the increasing demand for energy, has become an important matter in Algeria's agenda during the last decades.

Algeria has made the promotion of renewable energies one of its main challenges for meeting the growing energy demands in the next decades, by creating jobs while preserving hydrocarbon resources. In view to reach this goal, an ambitious strategy for encouraging and developing renewable energy was implemented.

This strategy aims to reduce national dependence on fossil fuels by developing the use of renewable energy resources, such as solar and wind energy in order to diversify energy sources and to promote the rational use of energy. In 2011, the Algerian government has adopted a plan for the Promotion of Renewable Energies on 03 February 2011.

This plan would use multiple renewable energy sources as solar and wind energy to replace gradually the use of fossil fuels (natural gas and oil) which currently are the main resource for the country's electricity generation. The first target is to increase the electricity production by the renewable energies to 40% of total energy consumption by 2030 [1]. In this context, many renewable energy projects will be developed and realized to achieve this objective. Among these projects, is the use of wind turbines to generate electricity. The starting point of any wind energy project is the resource assessment. It helps to identify suitable sites for wind turbines. The average wind speed and its annual frequency are the critical parameters that are used to calculate the net output energy of a wind turbine.

In the last decade, a lot of studies related to the wind characteristics and the wind power potential have been developed in many countries worldwide by researchers [2–9].

Akdag and Dinder [2] have proposed a new method, called power density method, to estimate Weibull parameters. They have compared it with the three most common ones, i.e, the graphic, method, the maximum likelihood and moment method and the numerical solution of energy pattern factor. Their results have indicated that the power density method is an adequate method to estimate Weibull parameters and it might have better suitability than other methods. If the power density and the mean wind speed are available, then it is very simple, using this method, to estimate the Weibull parameters.

Belu and Koracin [3] have estimated the wind potential in western Nevada by using wind, temperature, and pressure data over a period of four and half years from four 50 m tall towers. Their results have shown that the maximum seasonal wind speeds for all towers occur during the spring. Diurnal wind speed patterns for all seasons and months showed a minimum during the late morning and a maximum during the late afternoon.

Gökçek and Genc [4] investigated the wind energy generation by using a time-series approach method and the estimation of the unit energy cost by means of the levelised cost of electricity (LCOE) method. They applied this method for various wind energy conversion systems (small- and medium-scale WECS) in seven different sites located in the Central Anatolian Region in Turkey. Their results have shown that the 150 kW wind energy conversion system produces an energy output of 120,978 kWh per year in Pinarbasi at a hub height equal to 30 m.

Mostafaeipour [5] has analyzed the wind speed characteristics of some major cities in the province of Yazd which is located in the central part of Iran. He has determined the potential of wind power generation by using the hourly measured wind speed data at a height of 10 m, 20 m and 40 m for Yazd. He has found that most of the stations have an annual average wind speed lower than 4.5 m/s which is considered as too low for a wind turbines installation. The site of Herat has a higher wind energy potential with an annual wind speed average of 5.05 m/s and 6.86 m/s, respectively, at a height of 10 m and 40 m above ground level.

In another study, Mostafaeipoura et al. [6] have investigated the wind power potential for Shahrbabak in the Kerman province in Iran and they have studied the technical and economical feasibility of a wind turbine installation. With the average wind power density of 100 W/m^2, he has found that the site is not appropriate for the construction of large-scale wind power plants, but is suitable for employment of off-grid electrical and mechanical wind driven systems. The cost per kWh was 18 cents which is 5 cents more than the market price.

Aynur and Figen [7] have analyzed the wind potential and the wind farm feasibility in some locations of the coastal regions of Turkey. Their results have shown that Balıkesir and Canakkale have the highest values of annual mean wind speed. The mean annual value of Weibull shape parameter k is between 1.54 and 1.86 while the annual value of scale parameter c is between 2.52 m/s and 8.34 m/s. The maximum energy output was found for 2500 kW wind turbine (Nordex N80) in Balıkesir station and the minimum energy output was obtained for the 600 kW wind turbine (Suzlon S52) in Bartın.

Adaramola and Oyewola [8] have evaluated the wind energy potential in three locations in Oyo state, Nigeria and they have assessed the performance of small to medium commercial wind turbines. They have found that the monthly mean wind speeds in Oyo state ranges from 2.85 m/s to 5.20 m/s with a monthly mean power density between 27.08 W/m^2 and 164.48 W/m^2, and an annual mean power density is from 67.28 W/m^2 to 106.60 W/m^2.

Tiang and Ishak [9] have presented an investigation and an assessment of the wind energy potential in Penang Island. Their results have indicated that the connection of a large wind turbine system to the electrical network may not be commercially viable in Penang while a small-scale wind turbine system is more suitable.

In Algeria, a number of studies on wind speed distribution and wind potential assessment was performed [10–24]. The studies goes back to 1984 and we distinguish three different approaches. The first one concerns the establishment of wind atlases and wind resource maps of Algeria [10–14]. In this framework, we can cite the work of Said and Ibrahim in 1984 [10], followed by the works of Bensaid 1985 [11] which presented the Algerian program on wind energy.

In [12], a wind atlas was developed by using wind speed data from 37 locations. This atlas presented the results of the statistical study of these locations using the WASP computer software.

Kasbadji-Merzouk [13] presented a wind potential map of Algeria which characterizes the wind regimes of the country. She has identified the promising regions for wind energy development. The actualization of the wind map of Algeria has been carried out by adding the data for the site of Hassi R'Mel [14].

The second approach is the wind potential assessment and the design of wind energy conversion systems [15–20].

Himri et al. [15] has undertaken a statistical analysis of wind speeds at Tindouf in Algeria using the Risoe National Laboratory's Wind Atlas Analysis and Application Program (WAsP).

In another study, Himri et al. [16] has presented long-term analysis of wind speed data in terms of annual, seasonal and diurnal variations at Tindouf. The analysis has been based on data collected over a period of 08 years between 1976 and 1984.

Himri et al. [17] have presented an analysis of recently collected hourly wind data over a period of almost 5 years between 2002 and 2006, from four selected sites (Tindouf, Dely Brahim, Ouled Fayet and Marsa Ben M'hidi) in Algeria and they have carried out a preliminary evaluation of the wind energy potential.

In [18], Himri et al. have computed Weibull parameters for wind speed distribution at fifteen locations in Algeria on the basis of wind data covering a period of almost 10 years between 1977 and 1988. Their results have shown that the average wind speed at a height of

10 m above ground level is between 2.3 m/s and 5.9 m/s. The Weibull distributions parameters (c and k) were found to vary between 3.1 m/s and 7.2 m/s and 1.19–2.15, respectively. The authors have concluded that the Weibull distribution give a good fit to experimental data. An energy yield and economical analysis of a hypothetical wind farm consisting of 30 wind turbines of 1 MW rated power each at three different locations in Algeria (Adrar, Timimoun and Tindouf) was carried out by Himri et al. [19].

Djemai and Merzouk [20] have evaluated the wind potential of Adrar region using the Wasp software and they investigated the possibility to set up a wind farm of 10 MW in Adrar, a region located in the south of the country.

The third approach consists in studying the wind behavior. In this context, many studies were presented [21–24]. Youcef Ettoumi et al. [21] presented, on a monthly basis, the results of the modeling, of three-hourly wind speed and direction data recorded on the site of Oran during the 1982/92 period using both Markov chains and Weibull probability distributions.

In [22], Kasbadji Merzouk has defended her doctoral thesis about the vertical modeling of the wind profile in Algeria. Chellali et al. [23,24], has carried out a spectral study of the wind speed using time–frequency analysis.

In this study, the wind characteristic and the wind energy potential of 13 locations situated in different Algerian regions were analyzed using the wind speed data collected during the period 1976–1988. These locations are characterized by different geographical and climatological conditions. In addition, the performance of chosen commercial wind turbine models, designed for electricity generation and located in these sites are examined; at last an



Fig. 1. Distribution of meteorological stations over Algeria.

Table 1
Geographical data for the selected stations.

Station	Coordinates			
	Latitude (deg)	Longitude (deg)	Altitude (m)	Period
South region				
Adrar	27° 49′N	00° 17′W	263	1977–1988
Béchar	31° 37′N	02° 14′W	811	1976–1988
Ghardaia	32° 24′N	03° 48′E	468	1978–1987
In Amenas	28° 03′N	09° 38′E	561	1977–1988
Tamanrasset	22° 47′N	05° 31′E	1377	1976–1988
Highland region				
Tébessa	35° 25′N	08° 07′E	820	1976–1988
Sétif	36° 11′N	05° 15′E	1033	1981–1988
Djelfa	36° 41′N	03° 15′E	1144	1975–1987
Coastal area				
Annaba	36° 49′N	07° 49′E	05	1979–1988
Skikda	36° 53′N	06° 54′E	01	1976–1988
Bejaia	36° 43′N	05° 04′E	01	1977–1988
Alger	36° 43′N	03° 15′E	24	1979–1988
Oran	35° 38′N	00° 37′W	90	1979–1988

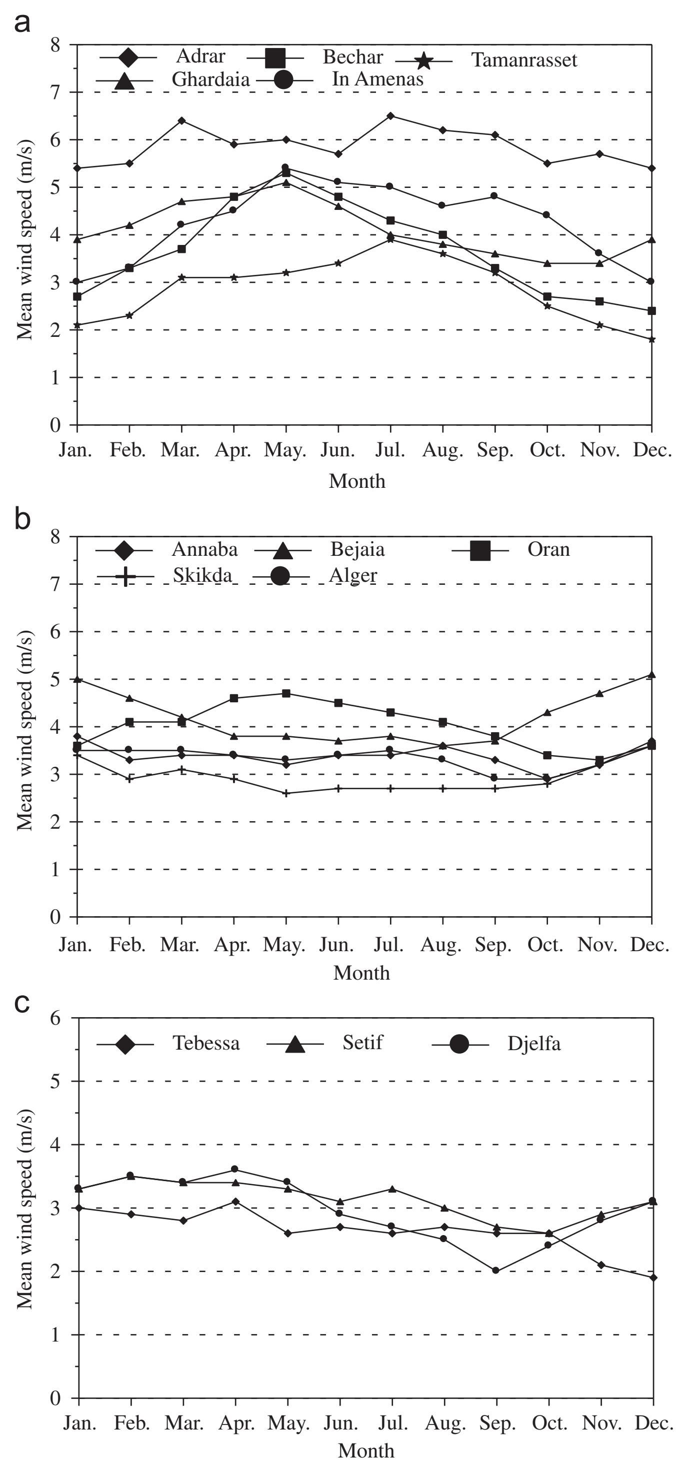


Fig. 2. Mean monthly wind speed for the sites in different regions (a) South region, (b) Highland region and (c) North (Coastal area) (at 10 m above ground).

economic evaluation of the wind energy in the selected sites is performed.

This study provides useful information for developing wind energy sites and planning economical wind turbines capacity for the electricity production in Algeria.

2. Wind characteristics

2.1. Wind data analysis

The knowledge of the characteristics of the wind regimes in any locations is important in the exploitation of wind resources. The present study is based on a data source measured at a height of 10 m above ground level.

The data were collected during the period 1976–1988 with different collection periods for each site [12]. Fig. 1 shows the locations of 13 stations which were chosen to cover the whole area of the country. The wind data for these meteorological stations were obtained from the Algerian Meteorological National Office. Table 1 shows the geographical coordinates and the period for which wind data were available for each station. The wind speed data were captured at 10 m height by a cup-generator anemometer and obtained on hourly basis, from which monthly wind speed and other wind speed parameters were determined.

The monthly and three hourly mean wind speed values calculated from the available data are presented in Figs. 2 and 3, respectively.

(a) *Monthly variation of the mean wind speed*
Fig. 2 Illustrates the variation of the mean monthly wind speed for the sites of different regions (Coastal, Highland and South).
The data analysis shows that in the southern part of Algeria, except the sites of Adrar and Tamanrasset, the monthly mean wind speed reaches its highest values during the period April–June. The lowest monthly wind speed occurrs, at most sites, during winter seasons.
For the northern sites (Coastal area), except Oran, where the mean wind speed reaches a maximum during the period April–June, the highest values of mean monthly wind speed occure during the winter season (December–January).
For the highland region, the figure shows that the three sites are characterized by a low wind speed all over the year. The values of mean monthly wind speed vary from 2 m/s to 3.5 m/s.
In addition, the data analysis shows that Adrar is the windiest site during all the year with an average annual wind speed around 6 m/s at 10 m above ground.

(b) *Three-hourly variation of the mean wind speed*
Fig. 3 Illustrates the average annual evolution of three-hourly wind speeds. It shows similar profiles for all the sites; with a decrease of wind speed during the night and an increase during daytime.

It can be noticed that most of the considered sites are windier in the afternoon than in the morning and the mean hourly wind speed begins to increase at 6 am at all sites.

As shown in this figure, the maximum wind speed occurs around 3 pm for all sites with the exception of Bejaia in the north and Adrar and In Amenas in the south.

Also, the wind speed data show that the site of Adrar has a good wind energy potential as the wind blows relatively at high speeds for long periods of time.

Indeed, at the site of Adrar, wind blows at speeds higher than 5 m/s during all the day and higher than 6 m/s during almost 10 h of the day (more than 40% of the time).

2.2. Wind speed frequency distribution

The wind speed distribution represents a good indicator of the wind potential; it can be used to estimate the available and the recoverable wind energy potential. This helps identify the suitable sites for wind energy projects.

The wind speed frequency distribution at a given site is either tabulated from wind speed data as a function of time or approximated by a probability distribution function based on measured data.

2.2.1. Frequency representation

The frequency distribution of the wind speeds can be derived from data measured at a given height. It represents the frequency with which the wind blows for each speed interval. Table 2 gives a summary of frequency distributions of wind speeds in terms of percentages at selected sites.

At Tamanrasset, Djelfa and Tebessa about 50% of the wind speed recorded is less than 3 m/s, which is the minimum (cut-in) speed of most wind turbines. This effectively rules out these stations for wind power utilization, as the wind machines would be at a stand-still for a large portion of the time. While at Adrar site, only 12% of the wind speed recorded was less than 3 m/s. Therefore, the wind turbine installed on this site can produce energy for about 88% of the time.

At the remaining sites, about 55–75% of their wind speeds lie between cut-in (3 m/s) and rated speed of 13 m/s. This means that a wind turbine with the above characteristics (3 m/s cut-in and 13 m/s rated) operates about 55–75% of the time at partial load.

Also, the table shows that the wind speeds for most of the sites used in the study rarely exceeds 13 m/s, speed for which this type of wind turbine produces its nominal power. Consequently, the wind turbines rarely operate at their nominal powers.

2.2.2. Mathematical representation of wind speed distribution

There are several probability functions, which can be used to identify suitable statistical distributions to represent wind speed frequency curve [25–28]. The Weibull and Rayleigh probability density functions are commonly used and widely adopted [25–34].

The Weibull function is a special case of the generalized gamma distribution and it is a two parameter distribution, while the Rayleigh distribution is a subset of the Weibull distribution and has only one parameter. This makes the Weibull function more versatile, and the Rayleigh function somewhat simpler to use.

The general form of the Weibull distribution for wind speed is given by [25,35–40]:

$$f(v)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

where $f(v)$ is the distribution probability of wind speed$v$, c is the Weibull scale parameter and k is the dimensionless Weibull shape parameter.

The Weibul parameters c and k can be calculated by the following approximations:

$$k=\left(\frac{\sigma}{\overline{v}}\right)^{-1,086} \quad (2)$$

$$c=\frac{\overline{v}}{\Gamma\left(1+\frac{1}{k}\right)} \quad (3)$$

where $\overline{v}$ and σ are respectively the mean wind speed and variance of the wind speed.

$$\overline{v}=\frac{1}{N_d}\sum_{i=1}^{N_d} v_i \text{ and } \sigma^2=\frac{1}{N_d}\sum_{i=1}^{N_d}(v_i-\overline{v})^2 \quad (4)$$

N_d is the data number.

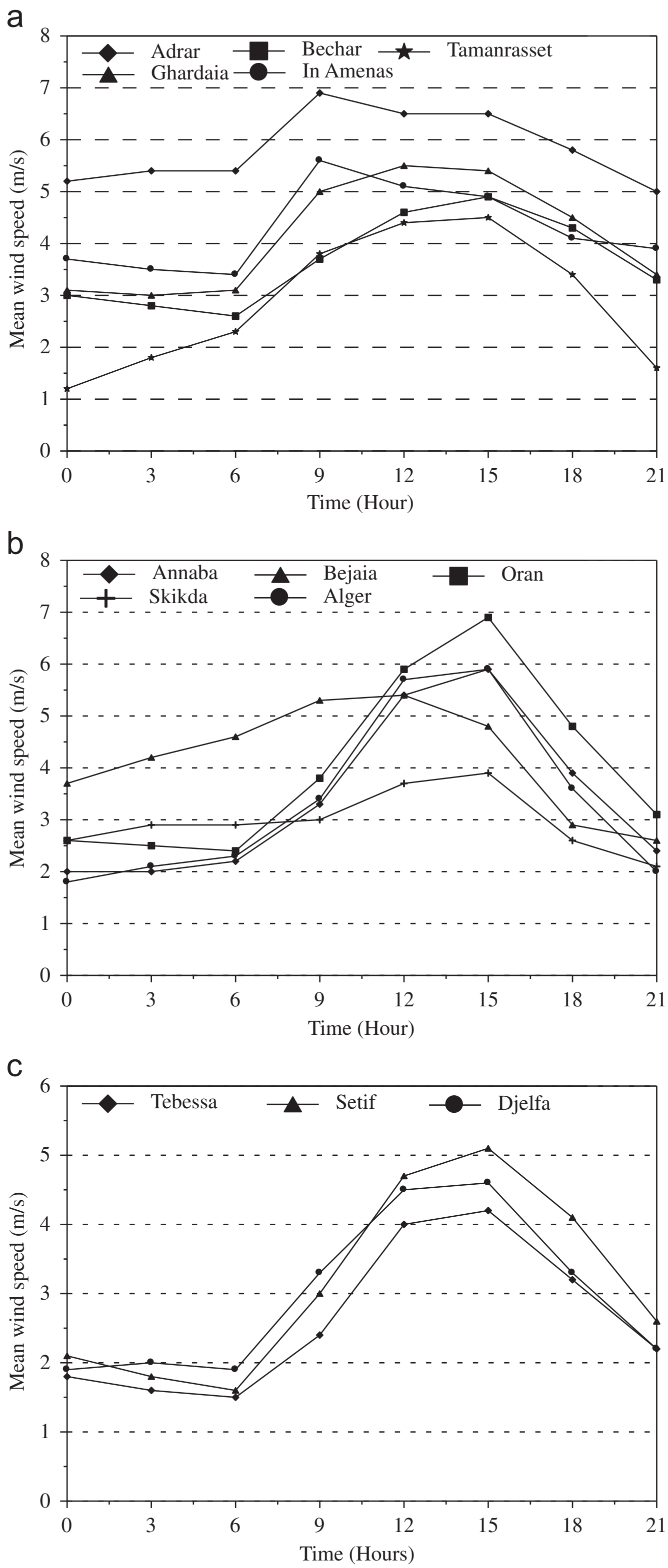


Fig. 3. Diurnal variation of wind speed for the sites in different regions (a) South, (b) Highland region and (c) Coastal area (at 10 m above ground).

Γ is the gamma function which is defined by the following integral equation:

$$\Gamma(x) = \int_0^{\infty} \exp(-t)t^{x-1}dt \text{ with } x \rhd 0 \quad (5)$$

The corresponding cumulative probability function of the Weibull distribution is given as

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (6)$$

Table 3 illustrates the values of the Weibull parameters and annual average wind speed for all sites. As it can be seen from this table, all the stations have an annual mean wind speed greater than 3.0 m/s except the sites of Tebessa and Tamanrasset that have 2.9 m/s.

Also this table shows that the most promising wind sites are: Adrar and In Amenas in the south, and Bejaia in the coastal region. Consequently, the south is windier than the north and the highland areas.

3. Wind power estimation and analysis

The wind resource at a location can be roughly described by the mean wind speed, but the wind power density provides a truer indication of a site's wind energy potential. The power density is proportional to the sum of the cube of the instantaneous wind speed and the air density. Due to this cubic term, two locations with the same average wind speed but different distributions can have very different wind power density values.

3.1. Available wind power

The mean wind power density is proportional to the mean cube of the wind speed, $\overline{v^3}$, as is expressed in the following equation:

$$\overline{P} = 0.5 \ \rho \overline{v^3} \quad (7)$$

where ρ is the air density ($\approx$ 1.225 kg m^{-3} for a temperature of 15 °C and a standard pressure of 1013 mb).

The mean value of the cube of the wind speed is given by [22,41]

$$\overline{v^3} = \int_0^{\infty} v^3 f(v) dv \quad (8)$$

Based on the frequency of occurrence of winds in different intervals, the mean cube of the wind speed can be expressed as [12,22,42,43]:

$$\overline{v^3} = \sum_i (v_i^3 f_i) \quad (9)$$

Using the Weibull parameters, the mean cube of the wind speed can be calculated with [22,42]

$$\overline{v^3} = c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (10)$$

Consequently, the mean available wind power density can be expressed in two different ways

Firstly, based on the wind speed data and their distribution, the mean wind power density can be calculated by the following expression:

$$\overline{P} = 0.5\rho \sum_{i=1}^{j} (v_i^3 f_i) \quad (11)$$

where v_i is the median wind speed of the i-th class, f_i is the frequency of occurrence of winds in the i-th class and j is the number of wind speed classes.

In terms of the Weibull parameters k and c, the mean wind power density may be also calculated by the following equation:

$$\overline{P} = 0.5\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (12)$$

Table 2
Relative frequency distribution of three hourly wind speeds.

Station	Wind speed frequencies (%)								
	0–3 m/s	3–5 m/s	5–7 m/s	7–9 m/s	9–11 m/s	11–13 m/s	13–15 m/s	15–17 m/s	> 17 m/s
South region									
Adrar	12	20	32	19	10	4	2	1	0
Béchar	42	22	17	9	5	2	1	1	0
Ghardaia	33	23	21	12	6	2	1	0	0
In Amenas	29	26	23	13	6	2	1	0	0
Tamanrasset	50	21	17	8	3	1	0	0	0
Highland region									
Tébessa	53	22	15	6	2	1	0	0	0
Sétif	42	29	18	8	3	1	0	0	0
Djelfa	48	23	17	8	3	1	0	0	0
Coastal region									
Annaba	42	26	19	9	3	1	0	0	0
Skikda	44	35	16	4	1	0	0	0	0
Bejaia	26	28	28	13	4	1	0	0	0
Alger	39	28	18	9	4	1	0	0	0
Oran	37	24	19	13	5	2	1	0	0

Table 3
Weibull distribution parameters at 10 m height [2].

Station	k	c (m/s)	v (m/s)
South region			
Adrar	2.15	7.2	5.9
Béchar	1.35	4.8	3.6
Ghardaia	1.65	5.6	4.1
In Amenas	1.86	5.6	4.3
Tamanrasset	1.46	4.0	2.9
Highland region			
Tébessa	1.35	3.7	2.6
Sétif	1.63	4.4	3.1
Djelfa	1.48	4.1	3.0
Coastal region			
Annaba	1.61	4.5	3.4
Skikda	1.76	4.1	3.0
Bejaia	2.17	5.6	4.2
Alger	1.61	4.7	3.3
Oran	1.58	5.1	4.0

However, the maximum wind power that can be extracted by the wind turbine, or the power coefficient, for an ideal wind turbine does not exceed the Betz limit (59%).

3.2. Extrapolation of wind power with height

Since the wind data measurements are generally recorded at a standard height of 10 m above the ground level and the wind turbines are generally installed at heights other than the standard height, the Weibull parameters at standard height must be adjusted to a hub height in order to estimate the wind power density available at this height.

Then, the values of the Weibull parameters (k and c) can be evaluated at any desired height, h_m, based on the records at the standard height of 10 m by the following equations [44,45]:

$$k(h_m) = \frac{k(10)}{1-0.088\ln(h_m/10)} \tag{13}$$

$$c(h_m) = c(10)\left(\frac{h_m}{10}\right)^{\alpha} \tag{14}$$

$$\alpha = 0.37-0.088\ln c(10) \tag{15}$$

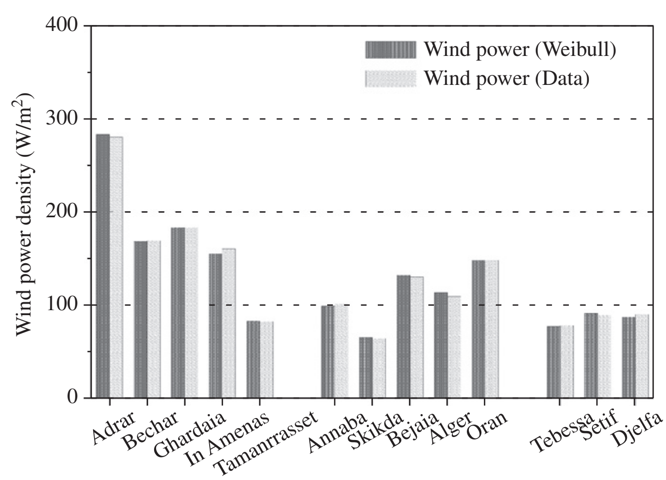


Fig. 4. Annual mean wind power density at 10 m height for different sites.

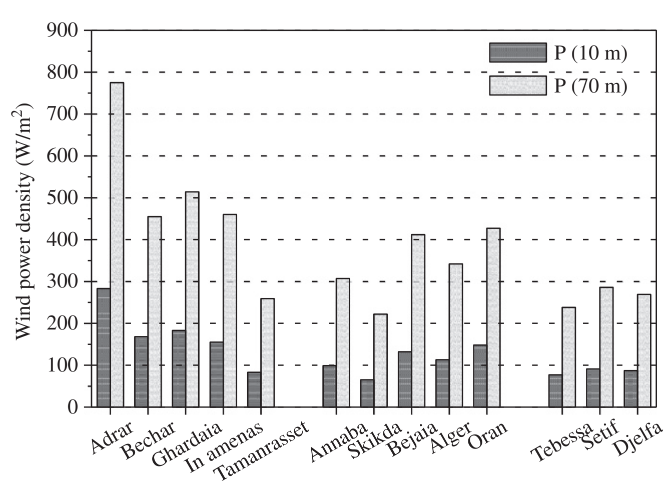


Fig. 5. Annual mean wind power density at the heights 10 and 70 m for different sites.

where $c(10)$ and $k(10)$ are the Weibull parameters at 10 m height, h_m is the hub height of the wind turbine and α is the power law exponent.

Using Eq. (11) and the data for wind speed distributions presented in Table 2, the mean wind power density can be calculated for all the selected sites.

Besides, the mean wind power density can be estimated from the Weibull parameters (c and k) given in Table 3 by using Eq. (12). Fig. 4 shows the mean wind power densities calculated from the frequency of occurrence of speed classes and those obtained from the Weibull parameters for all the sites.

The obtained results show that the estimation of the mean wind power density based on the Weibull parameters gives values very close to those calculated from the frequency of occurrence of speed classes. Consequently, the utilization of the Weibull parameters for the evaluation of wind energy potential may be adequate for these sites.

In addition, the wind power density can be estimated, at different heights, by using Eqs. (12)–(15). Fig. 5 presents the mean wind power density at a height of 10 and 70 m from the ground for the selected sites. The results show that the sites located in southern desert, except Tamanrasset, have an annual mean wind power density between 160–280 W/m^2 and 460–775 W/m^2 at the heights of 10 and 70 m, respectively. The highest values of mean wind power density of 280 and 775 W/m^2 at 10 and 70 m heights respectively are found at Adrar site. Consequently, the southern region has a good potential for developing wind energy sources, especially Adrar.

For the area of the highland, the three sites presented in this study have low wind power densities ranging from 78–90 W/m^2 to 238–286 W/m^2 at the heights of 10–70 m, respectively.

The coastal area is usually characterized by low wind power density, with the exception of Oran and Bejaia sites where the wind power density can exceed 130 W/m^2 at 10 m and 400 W/m^2 at 70 m.

In addition, the results show that the sites of Skikda and Annaba in the coastal region, Tebessa, Setif and Djelfa in the highland region and Tamanrasset in the southern region present low wind resources potential with power density not exceeding 100 W/m^2 and 310 W/m^2 at the heights of 10 and 70 m, respectively. That makes these sites unfavorable locations for the wind turbines installation for electricity generation.

In conclusion, it is interesting to note that:

- There is an important potential for wind energy exploitation in some areas of the country, especially, Adrar in the southern region.
- When the hub height increases from 10 m to 70 m, the available wind power density increases by a factor of 3.

4. Electricity generation and cost analysis

4.1. Wind turbine energy output

The following analysis is to help designers and users to choose the most suitable wind turbine.

The choice of these wind turbines used in this study were realized from an inventory of available machines in the market. A preparatory study was made in view to select the most efficient machines for the Algerian sites in estimating the energy output from the combination of weibull wind distribution of each site and the wind turbine power curve. From this first study, six machines were chosen and only the results obtained for these six wind turbines are presented in the continuation of this work. The energy outputs for these six different commercial wind turbines (each two of them have the same rated power but are different in their rated wind speed) were calculated.

The technical data of these six selected wind turbine types with different rated power is summarized in Table 4 [46–50] and their power curves are shown in Fig. 6.

Table 4
Technical data of different commercial wind turbines used in the analysis [25–29].

Turbine model	Cut-in wind speed (m/s)	Cut-off wind speed (m/s)	Rated wind speed (m/s)	Rated power (kW)	Hub height (m)	Rotor diameter (m)	Swept area (m^2)
Nordex N54/1000	3–4	25	14	1000	50.60.70	54	2290
Vergnet GEV HP1MW	3	25	15	1000	70	62	3019
Nordex S77/1500	3	25	13	1500	61.5–100	77	4657
Suzlon S82/1500	4	20	14	1500	70–78.5	82	5281
Fuhrlander FL 2500/90	3.5–4	25	13	2500	85–160	90	6362
Nordex N80/2500	3	25	15	2500	60.70.80	80	5027

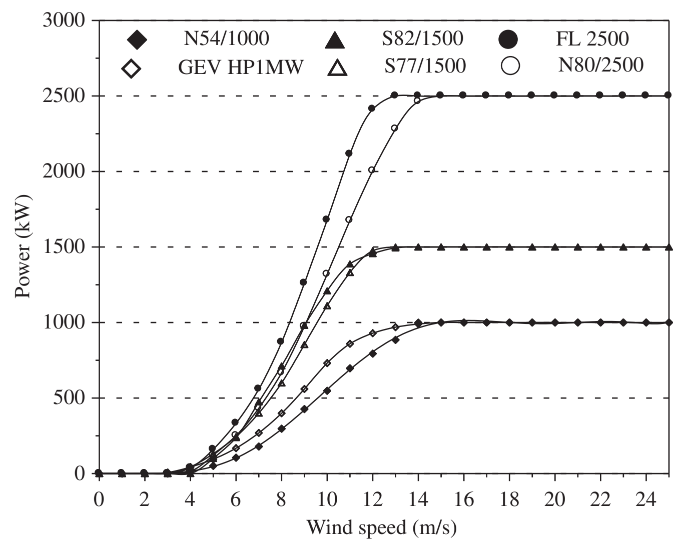


Fig. 6. Power curves for the selected wind turbines.

The annual energy was obtained using the power curve provided by the turbine manufacturer and one year wind duration data recorded at the sites. Since the wind data measurements are generally recorded at a standard height of 10 m above the ground level and the wind turbines are generally installed at height other than the standard height, the hourly mean wind speed values were calculated at that height using 1/7th power law.

Fig. 7 shows the simulation results of the yearly energy output from the selected wind turbines models of capacity 1000, 1500 and 2500 kW at all the locations presented in this study.

It can be seen from the figure that the yearly energy output ranges from about 180.9 MWh in Skikda (coastal region) with N54/1000 model to 9429.830 MWh in Adrar (southern region) using a Fuhrlander FL 2500 wind machine.

The wind turbines of capacity 2500 kW (Fuhrlander FL 2500 and Nordex N80/2500) were found to produce an energy output per year ranging from 535.9 MWh (Skikda) to 9429.8 MWh (Adrar).

In the case of a 1500 kW wind turbine (Suzlon S82/1500 and Nordex S77/1500), the annual energy output ranges from 378.1 MWh (Skikda) to 6370.549 MWh (Adrar). While in the case of 1000 kW wind turbine (Nordex N54/1000 and Vergnet GEV HP 1 MW), the generated annual wind energy in the considered stations varies between 180.9 MWh in Skikda and 4002.3 MWh in Adrar.

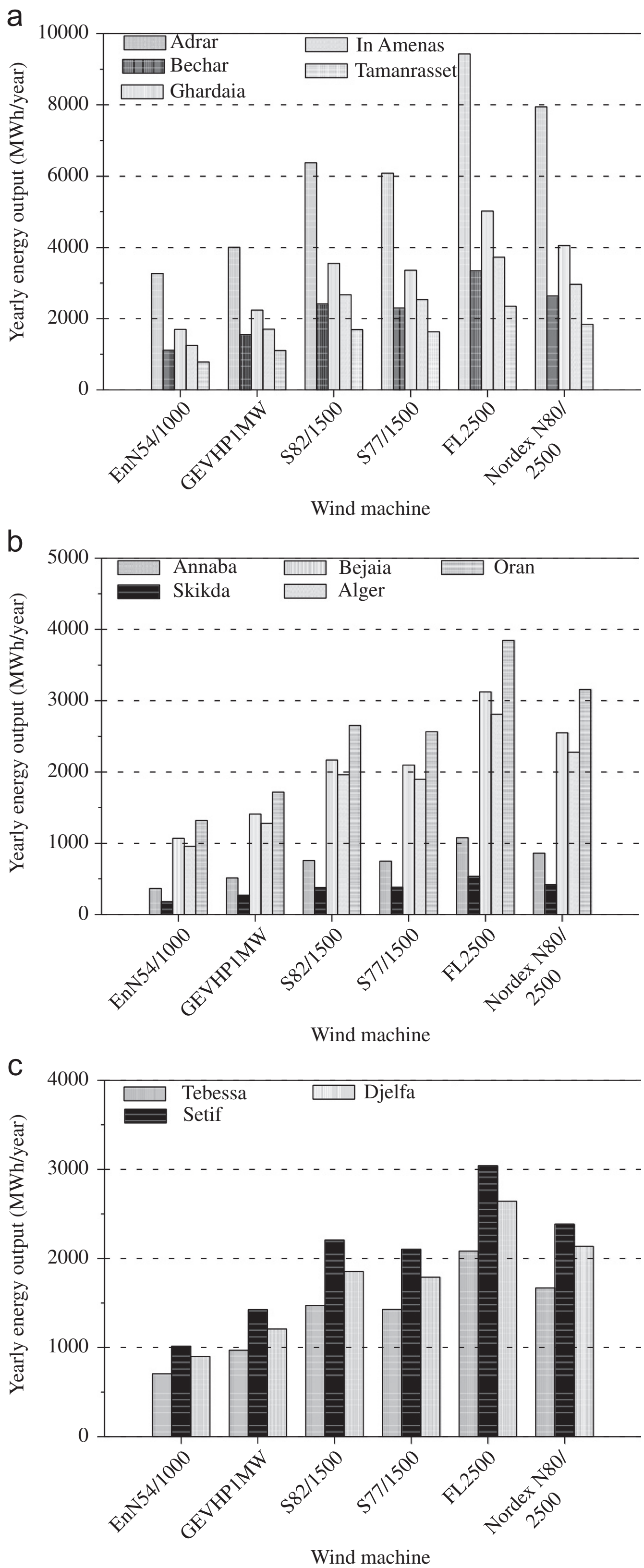


Fig. 7. Yearly energy output from wind turbines at the different sites; (a) South, (b) Coastal area and (c) Highland region.

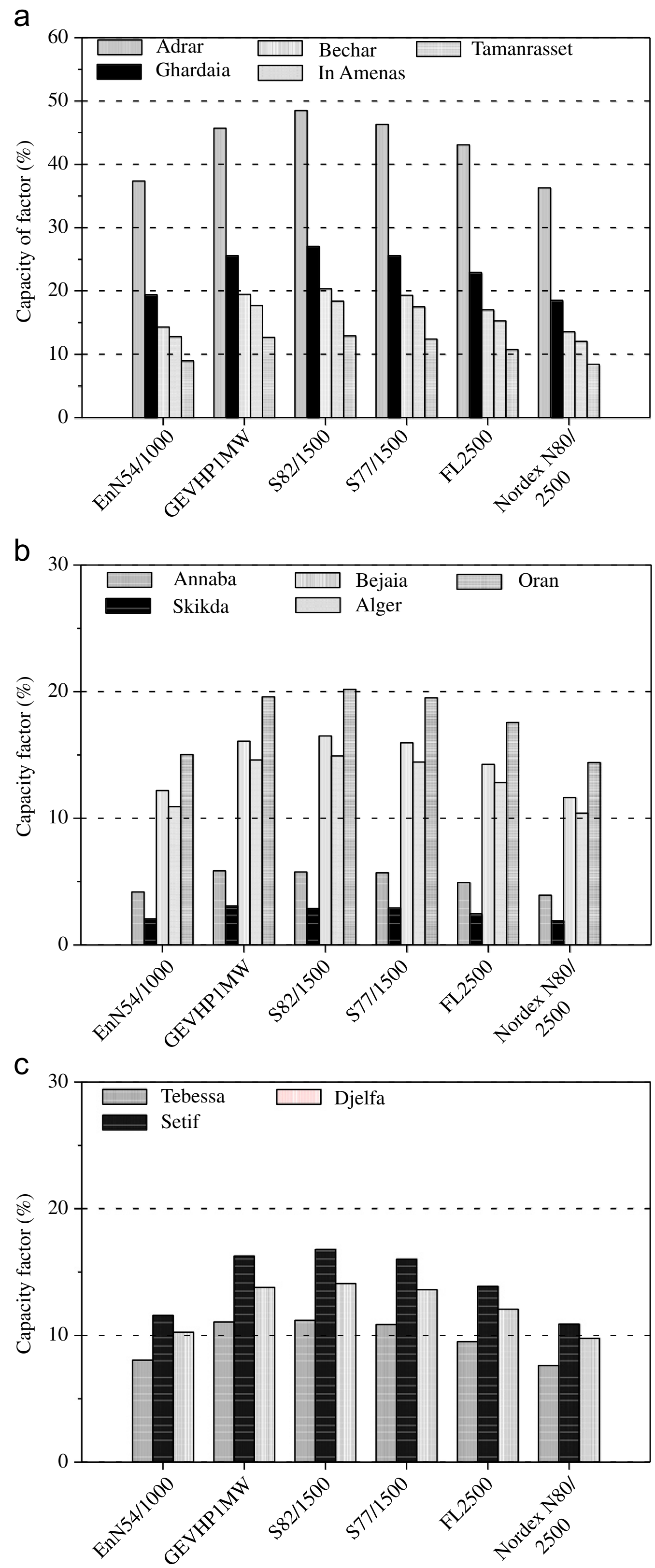


Fig. 8. Comparison of capacity factors obtained for different wind turbines at the different sites; (a) South, (b) Coastal area and (c) Highland region.

It is clear from Fig. 7 that Fuhrlander FL 2500 wind machine produces the maximum energy output at all the regions and Adrar is the best location among the considered sites, for harnessing the wind power, to generate energy while Ghardaia is the second best location.

Similarly the maximum energy output from the other five wind machines of capacity 1000 kW (Nordex N54/1000 and Vergnet GEV HP 1 MW) and 1500 kW (Suzlon S82/1500 and Nordex S77/1500),

was obtained for Adrar. The annual energy output for Adrar ranges from 3271.438 MWh using Nordex N54/1000 model to 9429.830 MWh using the Fuhrlander FL 2500 wind machine.

At the coastal and the highland regions, the maximum energy is found at the sites of Oran and Setif.

Also, we notice that more than 5000 MWh of wind energy was found for Adrar and Ghardaia from Fuhrlander FL 2500 wind machine. At most of the stations, the energy output was found to be between 2300 MWh and 5000 MWh.

The energy output is used to calculate the capacity factor of the wind machines. The capacity factor is one of the performance parameters of wind turbines which both the user and manufacturer need to know. It is defined as the fraction of the total energy delivered over a period, (one year in this study), divided by the maximum energy that could have been delivered if the turbine was used at maximum capacity over the entire period.

The annual capacity factors calculated for the different wind machines in all the regions are estimated and compared in Fig. 8.

The Suzlon S82/1500 model has the highest value among the models considered for all the sites. This is due to its rated wind speed and rotor diameter which are highest compared with other wind turbine models. The capacity factor values for this model were found to vary between 13% and 48% for the sites located in the southern region, between 11% and 17% for the sites on the highland region and between 3% and 20% for the sites situated along the coastal region. Furthermore, the Nordex N80/2500 model has the least capacity factors for each site.

As shown in Fig. 8, the highest capacity factor of 48% is obtained for the site of Adrar (southern region). The capacity factors for this site were found to lie between 36% and 48%.

The site of Ghardaia in the southern region is the second best site while comparing the capacity factors with those of other sites.

The capacity factors for the different wind turbine models for Skikda and Annaba (Coastal region), Tebessa (Highland region) and Tamanrasset (Southern region) indicate that they may not be good sites for wind energy development for electricity generation but small-scale applications. The lowest value of capacity factor is calculated as 1.91% for Nordex N80/2500 in the case of Skikda station.

From Fig. 8, it can also be seen that for the same rated power, the capacity factor is greater for wind turbine with a larger rotor diameter. For instance, the Vergnet GEV HP1MW wind machine (with a rotor diameter of 62 m) has a high capacity factor compared to the Nordex N54/1000 wind machine with a 54 m rotor diameter. Consequently, for the same rated power, the turbine with a larger diameter will generate more energy in a year than a turbine with a smaller diameter at all sites of the different regions (Fig. 7).

4.2. Economics analysis

The economic feasibility study is performed in terms of cost per unit (CPU), payback period (PBP) and return on investment (ROI).

4.2.1. Cost of energy

The estimation of cost per unit (CPU) is done by estimating the specific cost per kilowatt hour of energy produced by the wind turbine, which is expressed as the present value of costs (PVC) of the investment divided by the energy output during the wind turbine's lifetime (E_{tot}) [51–53]:

$$CPU = \frac{PVC}{E_{tot}} \tag{16}$$

Table 5
Range of specific cost of wind turbines based on the rated power [36–38].

Wind turbine size (kW)	Specific cost ($/kW)	Average specific cost ($/kW)
< 20	2200–3000	2600
20–200	1250–2300	1775
> 200	700–1600	1150

The present value of costs (PVC) of electricity produced per year can be calculated by the following formula [51,53–56]:

$$PVC = C_i + C_{omr}\left[\frac{(1+i)}{(r-i)}\right]\left[1-\left(\frac{(1+i)}{(1+r)}\right)^t\right] - S\left(\frac{(1+i)}{(1+r)}\right)^t \tag{17}$$

where C_i is the investment cost, C_{omr} is the operation, maintenance and repair cost, i is the inflation rate, r is the interest rate, t is the lifetime of the machine (in years) and S is the scrap value. The cost per unit kWh of energy produced by the various models of wind turbines was estimated based on the following assumptions [52–54]:

- The investment cost (C_i) includes the turbine price plus the cost of civil work and the connection cables to the grid (20% of the price).
- Operation, maintenance and repair cost (C_{omr}) was considered to be 25% of the annual cost of the turbine (machine price/lifetime).
- The interest rate (r) and inflation rate (i) were taken to be 8% and 6%, respectively.
- The machine lifetime (t) was assumed to be 20 years.
- Scrap value S was taken to be 10% of the investment cost (machine and civil work costs).

The specific turbine cost is dependent on the rated power but varies according to manufacturers [4,57,58]. Thus, choosing of the specific turbine cost can be done by considering a band interval (maximum and minimum values). Table 5 shows the specific cost of wind turbines for different size ranges [4,57,58]. As can be seen from this table, the cost per kW decreases with the increase of the wind turbine size. For machine size above 200 kW, the turbine cost can be taken as 1150 $/kW (the average between a minimum of 700 $/kW and maximum of 1600 $/kW).

The results of the CPU in all the sites for selected wind turbines are shown in Table 6. It can be observed that CPU depends on the specific cost of each wind turbine and site wind characteristics (represented by the turbine capacity factor).

According to the cost analysis it is seen that:

In the southern region, the cost of electricity per kWh produced using the wind machine of capacity 2500 kW varies between a minimum of 0.0202 $/kWh at Adrar and a maximum of 0.1034 $/kWh at Tamanrasset. Similarly the cost of electricity produced using the 1500 kW wind turbine varies between a minimum of 0.0179 $/kWh and a maximum of 0.0701 $/kWh corresponding to Adrar and Tamanrasset respectively. Whereas, it varies from 0.0190 $/kWh to 0.0971 $/kWh when produced using a 1000 kW wind machine.

In the Highland region, the cost of electricity produced from wind machine of capacity 2500 kW was found to be between a minimum of 0.0626 $/kWh at Setif a maximum of 0.1141 $/kWh at Tebessa. Similarly the cost of electricity produced using 1500 kW machine varies between a minimum of 0.0518 $/kWh and a maximum of 0.0800 $/kWh corresponding to Setif and Tebessa, respectively and it varies from 0.0534 $/kWh to 0.1079 $/kWh when produced using a 1000 kW wind machine.

In the coastal region, the costs of electricity production using 1000, 1500, and 2500 kW wind turbines were found to vary from

Table 6
Cost analysis for selected wind turbines ($/kWh).

Site	Turbine model	Yearly energy (MWh/year)	Capacity factor	Cost per unit ($/kWh)
Adrar	Nordex N54/1000	3271.5	0.3735	0.0233
	Vergnet GEV HP1MW	4002.3	0.4569	0.0190
	Suzlon S82/1500	6370.5	0.4848	**0.0179**
	Nordex S77/1500	6081.2	0.4628	0.0188
	Fuhrlander FL 2500/90	9429.8	0.4306	0.0202
	Nordex N80/2500	7942.9	0.3627	0.0240
Ghardaia	Nordex N54/1000	1698.5	0.1939	0.0448
	Vergnet GEV HP1MW	2239.8	0.2557	0.0340
	Suzlon S82/1500	3552.0	0.2703	**0.0322**
	Nordex S77/1500	3359.3	0.2557	0.0340
	Fuhrlander FL 2500/90	5019.4	0.2292	0.0379
	Nordex N80/2500	4053.4	0.1851	0.0470
Bechar	Nordex N54/1000	1117.7	0.1276	0.0681
	Vergnet GEV HP1MW	1551.4	0.1771	0.0491
	Suzlon S82/1500	2415.2	0.1838	**0.0473**
	Nordex S77/1500	2297.1	0.1748	0.0497
	Fuhrlander FL 2500/90	3341.3	0.1526	0.0570
	Nordex N80/2500	2634.9	0.1203	0.0722
In Amenas	Nordex N54/1000	1251.8	0.1429	0.0608
	Vergnet GEV HP1MW	1704.5	0.1946	0.0447
	Suzlon S82/1500	2669.9	0.2032	**0.0428**
	Nordex S77/1500	2535.4	0.1930	0.0450
	Fuhrlander FL 2500/90	3725.4	0.1701	0.0511
	Nordex N80/2500	2965.4	0.1354	0.0642
Tamanrasset	Nordex N54/1000	784.4	0.0895	0.0971
	Vergnet GEV HP1MW	1107.9	0.1265	0.0687
	Suzlon S82/1500	1695.4	0.1290	**0.0674**
	Nordex S77/1500	1628.7	0.1239	0.0701
	Fuhrlander FL 2500/90	2347.2	0.1072	0.0811
	Nordex N80/2500	1841.6	0.0841	0.1034
Annaba	Nordex N54/1000	365.9	0.0418	0.2081
	Vergnet GEV HP1MW	512.6	0.0585	**0.1485**
	Suzlon S82/1500	756.9	0.0576	0.1509
	Nordex S77/1500	747.1	0.0569	0.1529
	Fuhrlander FL 2500/90	1078.0	0.0492	0.1766
	Nordex N80/2500	860.5	0.0393	0.2212
Skikda	Nordex N54/1000	180.9	0.0206	0.4210
	Vergnet GEV HP1MW	269.4	0.0308	**0.2826**
	Suzlon S82/1500	378.1	0.0288	0.3020
	Nordex S77/1500	383.7	0.0292	0.2976
	Fuhrlander FL 2500/90	535.9	0.0245	0.3551
	Nordex N80/2500	418.7	0.0191	0.4546
Bejaia	Nordex N54/1000	1067.7	0.1219	0.0713
	Vergnet GEV HP1MW	1409.2	0.1609	0.0540
	Suzlon S82/1500	2167.9	0.1650	**0.0527**
	Nordex S77/1500	2096.8	0.1596	0.0545
	Fuhrlander FL 2500/90	3123.9	0.1426	0.0609
	Nordex N80/2500	2549.0	0.1164	0.0747
Algiers	Nordex N54/1000	956.6	0.1092	0.0796
	Vergnet GEV HP1MW	1278.5	0.1460	0.0595
	Suzlon S82/1500	1960.7	0.1492	**0.0582**
	Nordex S77/1500	1897.1	0.1444	0.0602
	Fuhrlander FL 2500/90	2808.1	0.1282	0.0678
	Nordex N80/2500	2276.5	0.1040	0.0836
Oran	Nordex N54/1000	1317.6	0.1504	0.0578
	Vergnet GEV HP1MW	1716.2	0.1959	0.0444
	Suzlon S82/1500	2651.5	0.2018	**0.0431**
	Nordex S77/1500	2563.5	0.1951	0.0445
	Fuhrlander FL 2500/90	3844.8	0.1756	0.0495
	Nordex N80/2500	3154.4	0.1440	0.0603
Djelfa	Nordex N54/1000	899.0	0.1026	0.0847
	Vergnet GEV HP1MW	1207.7	0.1379	0.0630
	Suzlon S82/1500	1851.4	0.1409	**0.0617**
	Nordex S77/1500	1789.6	0.1362	0.0638
	Fuhrlander FL 2500/90	2642.3	0.1207	0.0720
	Nordex N80/2500	2137.3	0.0976	0.0891
Tebessa	Nordex N54/1000	705.3	0.0805	0.1079
	Vergnet GEV HP1MW	969.2	0.1106	0.0785
	Suzlon S82/1500	1471.7	0.1120	**0.0776**

Table 6 (*continued*)

Site	Turbine model	Yearly energy (MWh/year)	Capacity factor	Cost per unit ($/kWh)
	Nordex S77/1500	1426.7	0.1086	0.0800
	Fuhrlander FL 2500/90	2082.2	0.0951	0.0914
	Nordex N80/2500	1668.3	0.0762	0.1141
Setif	Nordex N54/1000	1015.0	0.1159	0.0750
	Vergnet GEV HP1MW	1425.6	0.1627	0.0534
	Suzlon S82/1500	2206.6	0.1679	**0.0518**
	Nordex S77/1500	2103.9	0.1601	0.0543
	Fuhrlander FL 2500/90	3040.3	0.1388	0.0626
	Nordex N80/2500	2386.0	0.1090	0.0798

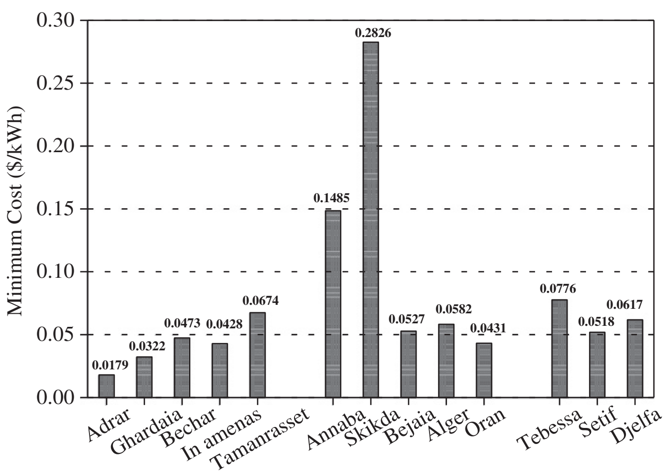


Fig. 9. Minimum cost per kWh of energy generated from chosen wind turbines at the different sites.

0.0444 $/kWh to 0.4210 $/kWh, 0.0431 to 0.3020 $/kWh and 0.0495 to 0.4546 $/kWh, respectively.

From Table 6, one can notice that the minimum cost of unit energy per kWh of energy is obtained with the Suzlon S82/1500 model for all the sites except for Skikda and Annaba in the coastal region where the minimum cost is obtained with the Vergnet GEV HP1MW model.

Fig. 9 gives the minimum cost of electricity per kWh at each location, using all the wind machines considered in this study.

As it can be seen from the figure, the minimum cost per kWh of energy found does not exceed 0.05 $/kWh at all sites of southern region, except Tamanrasset where the cost of producing electricity per kWh is found to be 0.0674 $/kWh. The minimum cost of 0.0179 $/kWh is obtained for Adrar using the Suzlon S82/1500 model. The site of Ghardaia is the second best site with 0.0322 $/kWh.

At the coastal region, the minimum cost of electricity generated was found to be 0.0431 $/kWh at Oran, while the corresponding maximum was 0.2826 $/kWh at Skikda.

Similarly at highland region, the lowest cost electricity produced, for all the wind machines considered in this study, was obtained at Setif with 0.0518 $/kWh.

As a result, the minimum cost of energy output in the different regions considered in this study is found to be 0.0179 $/kWh at Adrar.

Moreover, the electricity generation cost per kWh from wind machines in almost all sites considered does not exceed 0.060 $/kWh which is a very competitive price compared to the price of electricity paid by the consumer of domestic sector in Algeria (0.054 $/kWh). This cost will be decreased further as the costs of wind energy systems will be lowered based on the development of wind energy technology.

In addition to the estimation of the cost per unit, two other parameters are calculated in the economic analysis: Payback period (PBP), and return on investment (ROI).

4.2.2. Payback period

The payback period reflects the length of time required for a projects cumulative revenues to return its investment through the annual cash flow. A more attractive investment is one with a shorter payback period. There are two ways to calculate the payback period; the simple Payback (SPB) and the discounted Payback (DPB) [59].

In this study, the discounted Payback method is used to determine the time of return on investment of the project. For energy projects, the DPB can be obtained from the following expression [59,60]:

$$\mathrm{DPB} = \frac{C_i}{[\mathrm{AAR} - C_{omr}]} \tag{18}$$

with

$$\mathrm{AAR} = E_{an}\mathrm{PS} \tag{19}$$

where C_i is the investment cost, AAR is the average annual revenue based on hourly production, C_{omr} is the operations and maintenance cost, E_{an} is the annual energy production, and PS is the price at which the utility sells energy to the consumer. In this study, *PS* is assumed to be 0.108 $/kWh that represents 200% the price of electricity paid by the consumer of domestic sector in Algeria.

4.2.3. Return on investment

An another economic indicator is computed in this study. It consists on the return on investment (ROI). The ROI is expressed as a percentage and is based on returns over an associated time period, usually one year. It represents the ratio between The net present value of benefits and the total present value of costs [61,62].

$$\mathrm{ROI} = \frac{\mathrm{PVB} - \mathrm{PVC}}{\mathrm{PVC}} \tag{20}$$

where PVB is the present value of benefits over the lifetime of the wind projects and PVC is the present value of costs.

The DPB and ROI for all the locations using the wind turbine models considered in this study are shown in Table 7.

The simulation results showed that at all sites, the minimum payback periods are found for the Suzlon S82/1500 model. Adrar, in the southern region, is found to be the best one in terms of the payback periods for all wind turbine models

At the southern region, the payback periods found for different wind turbine models do not exceed 13.9 years at all sites, except

Table 7
Comparison of Payback period (DPB) and return on investment (ROI) using six selected wind machines at different sites.

Site	Turbine model	Payback period (year)	Return on investment (%)
Adrar	Nordex N54/1000	4.1	284
	Vergnet GEV HP1MW	3.3	369
	Suzlon S82/1500	**3.1**	398
	Nordex S77/1500	3.3	375
	Fuhrlander FL 2500/90	3.5	342
	Nordex N80/2500	4.2	273
Ghardaia	Nordex N54/1000	8.2	99
	Vergnet GEV HP1MW	6.1	163
	Suzlon S82/1500	**5.7**	178
	Nordex S77/1500	6.1	163
	Fuhrlander FL 2500/90	6.8	135
	Nordex N80/2500	8.6	90
Bechar	Nordex N54/1000	13.0	31
	Vergnet GEV HP1MW	9.0	82
	Suzlon S82/1500	**8.7**	89
	Nordex S77/1500	9.1	80
	Fuhrlander FL 2500/90	10.6	57
	Nordex N80/2500	13.9	24
In Amenas	Nordex N54/1000	11.4	47
	Vergnet GEV HP1MW	8.1	100
	Suzlon S82/1500	**7.8**	109
	Nordex S77/1500	8.2	98
	Fuhrlander FL 2500/90	9.4	75
	Nordex N80/2500	12.1	39
Tamanrasset	Nordex N54/1000	19.6	−8
	Vergnet GEV HP1MW	13.1	30
	Suzlon S82/1500	**12.8**	33
	Nordex S77/1500	13.4	27
	Fuhrlander FL 2500/90	15.9	10
	Nordex N80/2500	21.2	−14
Annaba	Nordex N54/1000	54.9	−57
	Vergnet GEV HP1MW	**33.7**	−40
	Suzlon S82/1500	34.4	−41
	Nordex S77/1500	35.0	−42
	Fuhrlander FL 2500/90	42.9	−49
	Nordex N80/2500	60.5	−60
Skikda	Nordex N54/1000	267.6	−79
	Vergnet GEV HP1MW	**93.8**	−68
	Suzlon S82/1500	107.4	−70
	Nordex S77/1500	104.1	−70
	Fuhrlander FL 2500/90	157.2	−75
	Nordex N80/2500	371.8	−80
Bejaia	Nordex N54/1000	13.7	25
	Vergnet GEV HP1MW	10.0	65
	Suzlon S82/1500	**9.7**	69
	Nordex S77/1500	10.1	64
	Fuhrlander FL 2500/90	11.4	47
	Nordex N80/2500	14.4	20
Algiers	Nordex N54/1000	15.5	12
	Vergnet GEV HP1MW	11.2	50
	Suzlon S82/1500	**10.9**	53
	Nordex S77/1500	11.3	48
	Fuhrlander FL 2500/90	12.9	32
	Nordex N80/2500	16.4	7
Oran	Nordex N54/1000	10.8	54
	Vergnet GEV HP1MW	8.1	101
	Suzlon S82/1500	**7.8**	107
	Nordex S77/1500	8.1	100
	Fuhrlander FL 2500/90	9.1	80
	Nordex N80/2500	11.3	48
Djelfa	Nordex N54/1000	14.5	19
	Vergnet GEV HP1MW	9.9	67
	Suzlon S82/1500	**9.6**	72
	Nordex S77/1500	10.1	64
	Fuhrlander FL 2500/90	11.8	43
	Nordex N80/2500	15.6	12
Tebessa	Nordex N54/1000	16.7	5
	Vergnet GEV HP1MW	11.9	42
	Suzlon S82/1500	**11.6**	45

Table 7 (*continued*)

Site	Turbine model	Payback period (year)	Return on investment (%)
	Nordex S77/1500	12.1	40
	Fuhrlander FL 2500/90	13.8	24
	Nordex N80/2500	17.7	0
Setif	Nordex N54/1000	22.3	−17
	Vergnet GEV HP1MW	15.3	14
	Suzlon S82/1500	**15.1**	15
	Nordex S77/1500	15.6	12
	Fuhrlander FL 2500/90	18.3	−2
	Nordex N80/2500	23.9	−22

Tamanrasset where the payback periods is found to be 21.8 years for the Nordex N80/2500 wind turbine model.

The minimum payback of 3.1 years is obtained for the Suzlon S82/1500 wind turbine model at Adrar. A shorter payback period means a desirable investment.

For *the area of the highland*, the payback period ranges from 9.6 years using Suzlon S82/1500 at Djelfa to 23.9 years using Fuhrlander FL 2500 wind machine at Setif.

At the coastal region, except Skikda, the payback periods for the different wind turbine models considered in this study were found to vary from 7.8 years at Oran site for the Suzlon S82/1500 model to 60.5 years at Annaba for the Nordex N80/2500.

The ROI for all the locations using six wind turbine models is also presented in Table 7. As shown in this table, the ROI values were found to be positive for all the wind turbine models at all sites, except Annaba and Skikda, at the coastal area, where the ROI was found to be negative for all the wind turbine models.

Positive values of ROI demonstrate that the project is feasible. In case the ROI is negative, it means the costs incurred are higher than the benefits over the lifetime of the wind projects. This indicates a loss and this investment should not be considered.

The simulation results showed that the best ROI for all the wind turbine models were found at Adrar in the southern region, at Oran in the coastal region and at Djelfa in the highland area.

As can be seen from Table 7, the return on investment for all the wind turbine models at the southern region is relatively high compared to that at the other regions. For the Suzlon S82/1500 wind turbine, the ROI was found to be 398%, 178%, 109% and 89% at Adrar, Ghardaia, In Amenas and Bechar sites, respectively.

The negative values of ROI at Annaba and Skikda sites are an indicative of unprofitable wind projects for all types of wind turbine at these two sites.

The important result derived from the current study encourages the construction of wind farms in the southern region especially Adrar for electricity generation. In addition, the usage of the wind turbine model "Suzlon S82/1500 of capacity 1.5 MW is highly recommended".

4.3. Maintenance problems and necessity of diagnosis for wind turbines

Wind turbines must be maintained and repaired consistently to prevent failures that may occur. The maintenance and management of large-scale wind power is critical for continuous operations. Most large-scale wind turbines are installed in remote and offshore locations, making it difficult to arrange maintenance. In addition, the nacelle, which houses the turbine's mechanical parts, sits at high height in the air and is difficult to access.

For the wind turbines installed and generating electricity in the desert, what is the case for an important part of the studied sites in this paper, many further maintenance problems occur because the desert climate includes high temperatures, high day/night gradients of temperatures, dryness and mainly sandstorms.

Dust, sand, and temperatures extremes cause an estimated percent of failures and increase in repair parts required to maintain wind turbine and increasing the O&M costs. The impact of dust/sand layer on blade have two threads; first, reduce the production performance due to mass and change the aerofoil shape of blade, that lead to increasing the needed lifting force. Second, it is acting as abrasive particulars on blade and nacelle bodies. Another difficulty caused by the sand consists on sealing in order to avoid the seizing up system.

In addition, the combination of heat and dryness makes plastic parts in the drive train particularly susceptible to breakage. The high temperature gradient between day and night induces thermal expansion phenomena which are harmful for materials and electronics.

To maintain the gearbox properly, it should be well-lubricated and replace oil filters at regular intervals to combat foreign particles.

Indeed, from the fact that large wind turbines are very difficult to access and submitted to extreme conditions, the requirement for remote monitoring and visual inspection becomes more important to maintain appropriate turbine availability levels.

Consequently, there is a strong need to reduce the maintenance costs and the operating cost. The improvement of the reliability and availability of wind turbine in such difficult conditions requires the minimization and the ability to predict maintenance operations.

To achieve this objective, fault detection and diagnosis play an important industrial role. They contribute, by early detection and early to earn points and availability of production capital invested in production facilities

This will remove certain difficulties due to problems of accessibility and will detect an early, mechanical defects and/or providing electrical failures of different components (electrical and mechanical) of the wind, facilitating a proactive response, minimizing sudden stops caused by breakdowns and consequently maximizing productivity. The most effective method for reducing these costs is to continuously monitor a state of the wind and especially its electric generator for use in diagnosis.

These O&M problems and the necessity to develop an efficient fault detection and diagnosis system can increase the O&M cost for most cases of the sites studied here for wind farms installation with high consequences on the kWh production cost and on the payback period.

5. Conclusion

In this study, the wind energy potential and economic analysis in thirteen selected locations in Algeria were investigated. The following conclusions can be drawn from the results of the present study:

- The sites located in the southern region, except Tamanrasset, are characterized by a good wind potential compared to other

regions. The highest values of mean wind power density of 775 W/m^2 at 70 m heights is found at Adrar.
- The coastal area is usually characterized by a low wind power density, with the exception of Oran and Bejaia sites where the wind power density can reach 150 W/m^2 and 400 W/m^2 at 10 and 70 m heights respectively.
- For the area of highland, the three sites presented in this study have low wind power densities ranging from 77–90 W/m^2 to 138–286 W/m^2 at the heights of 10 and 70 m, respectively.
- When the hub height increases from 10 m to 70 m, the available wind power density increases by a factor of 3.
- In term of energy production and capacity factor, Adrar is the best location among the considered sites, for harnessing the wind power to generate electrical energy while Ghardaia is the second best site. The maximum energy output of 9429.830 MWh is found for the Fuhrlander FL 2500 wind machine at Adrar.
- The Suzlon S82/1500 model has the highest value among the models considered for all the sites. The capacity factor values for this wind machine model were found to vary between 13% and 48% for the sites located in the southern region, between 11% and 17% for the sites on the highland region and between 3% and 20% for the sites situated along the coastal region
- For the same rated power, the turbine with the larger diameter will generate more energy in a year than a turbine with the smaller diameter.

According to the cost analysis, we get:

- The minimum cost per kWh of electricity generated from the wind machines considered in this study, is found to be 0.0179 $/kWh at Adrar for the southern region, 0.0431 $/kWh at Oran for the coastal region and 0.0518 $/kWh at Setif for the highland region.
- The electricity generation cost per kWh from wind machines in almost all the considered sites is a very competitive price compared to the price of electricity paid by the consumer of the domestic sector in Algeria.
- The Suzlon S82/1500 wind turbine among all the models considered in this study for same hub heights (70 m) is the most attractive in terms of the cost per kWh.
- The wind resource appears to be suitable for electricity generation in the south area of the country and it could provide a viable substitute to diesel oil for electricity production.

Finally, for electricity generation, the Suzlon S82/1500 wind turbine model is recommended for wind farms constructing in the southern region especially Adrar.

References

[1] 〈http://portail.cder.dz〉; 2011.
[2] Akdag SA, Dinler A. A new method to estimate Weibull parameters for wind energy applications. Energy Conversion and Management 2009;50:1761–6.
[3] Belu R, Koracin D. Wind characteristics and wind energy potential in western Nevada. Renewable Energy 2009;34:2246–51.
[4] Gökçek M, Genc MS. Evaluation of electricity generation and energy cost of wind energy conversion systems (WECSs) in Central Turkey. Applied Energy 2009;86:2731–9.
[5] Mostafaeipour A. Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran. Renewable and Sustainable Energy Reviews 2010;14:93–111.
[6] Mostafaeipour A, Sedaghatb A, Dehghan-Niric AA, Kalantarc V. Wind energy feasibility study for city of Shahrbabak in Iran. Renewable and Sustainable Energy Reviews 2011;15:2545–56.
[7] Aynur U, Figen B. Assessment of wind power potential for turbine installation in coastal areas of Turkey. Renewable and Sustainable Energy Reviews 2010;14:1901–12.
[8] Adaramola MS, Oyewola OM. Evaluating the performance of wind turbines in selected locations in Oyo state, Nigeria. Renewable Energy 2011;36: 3297–3304.
[9] Tiang TL, Ishak D. Technical review of wind energy potential as small-scale power generation sources in Penang Island Malaysia. Renewable and Sustainable Energy Reviews 2012;16:3034–42.
[10] Said M, Ibrahim A. Energy in the Arab world. Energy 1984;9(3):217–38.
[11] Bensaid H. The Algerian program on wind energy. In: Proceeding of WEAC. Oxford; 1985. p. 21–7.
[12] Hammouche R. Atlas Vent de l'Algérie/ONM. Alger: Office des Publications Universitaires (OPU); 1990.
[13] Kasbadji Merzouk N. Wind energy potential of Algeria. Renewable Energy 2000;21:5536–62.
[14] Chellali F, Khellaf A, Belouchrani A, Recioui. A. A contribution in the actualization of wind map of Algeria. Renewable and Sustainable Energy Reviews 2011;15:993–1002.
[15] Himri Y, Himri S, Boudghene Stambouli A. Wind power resource in the south-western region of Algeria. Renewable and Sustainable Energy Reviews 2010;14:554–6.
[16] Himri Y, Rehman S, Agus Setiawan A, Himri S. Wind energy for rural areas of Algeria. Renewable and Sustainable Energy Reviews 2012;16:2381–5.
[17] Himri Y, Himri S, Boudghene Stambouli A. Assessing the wind energy potential projects in Algeria. Renewable and Sustainable Energy Reviews 2009;13: 2187–2191.
[18] Himri Y, Himri S, Boudghene Stambouli A. Weibull parameters for wind speed distribution at fifteen locations in Algeria. Nova Science Publishers; 2009 978-1-60692-572-580.
[19] Himri Y, Rehman S, Draoui B, Himri S. Wind power potential assessment for three locations in Algeria. Renewable and Sustainable Energy Reviews 2008;12:2495–504.
[20] Djamai M, Kasbadji Merzouk N. Wind farm feasibility study and site selection in Adrar, Algeria. Energy Procedia 2011;6:136–42.
[21] Youcef Ettoumi F, Sauvageot H, Adane AEH. Statistical bivariate modeling of wind using first-order Markov chain and Weibull distribution. Renewable Energy 2003;28:1787–802.
[22] Kasbadji Merzouk N. Evaluation du gisement énergétique éolien contribution a la détermination du profil vertical de la vitesse du vent en Algérie. Thèse doctorat. Tlemcen: Université Abou bekr Belkaid; 2006.
[23] Chellali F, Khellaf A, Belouchrani A. Application of time–frequency representationin the study of the cyclical behavior of wind speed in Algeria: wavelet transform. Stochastic Environmental Research and Risk Assessment 2010;8:1233–9.
[24] Chellali F, Khellaf A, Belouchrani A. Wavelet spectral analysis of the temperature and wind speed data at Adrar, Algeria. Renewable Energy 2010;35:1214–9.
[25] Isaac Lun YF, Joseph Lam. C. A study of weibull parameters using long-term wind observation. Renewable Energy 2000;20:145–53.
[26] Sahin AD, Sen Z. First-order Markov chain approach to wind speed modelling. Journal of Wind Engineering and Industrial Aerodynamics 2001;89: 263–269.
[27] Parlange MB, Katz RW. An extended version of the Richardson model for simulating daily weather variables. Journal of Applied Meteorology 2000;39:610–22.
[28] Diaf S. Intégration des systèmes à sources renouvelables d'énergie pour la production décentralisée d'électricité en site isolé. Thèse de doctorat en Sciences. Ecole Nationale Supérieure Polytechnique Algérie: Département d'Electronique, Laboratoire des Dispositifs de Communication et de Conversion Photovoltaïque; 2009.
[29] Garcia A, Torres JI, Prieto E, De Francisco A. Fitting probability density distributions: a case study. Solar Energy 1998;62(2):139–44.
[30] Jamil M, Parsa S, Majidi M. Wind power statistics and an evaluation of wind energy density. Renewable Energy 1995;6:623–8.
[31] Justus CG, Hargraves WR, Mikhail A, Graber D. Methods of estimating wind speed frequency distributions. Journal of Applied Meteorology 1978;17: 350–353.
[32] Kose R, Ozgur MA, Erbas O, Tugcu. A. The analysis of wind data and energy potential in Kutahya, Turkey. Renewable and Sustainable Energy Reviews 2004;8:277–88.
[33] Rehman S. Wind energy resources assessment for Yanbo, Saudi Arabia. Energy Conversion and Management 2004;45:2019–32.
[34] Vogiatzis N, Kotti K, Spanomitsios KS, Stoukides M. Analysis of wind potential and characteristics in North Aegean, Greece. Renewable Energy 2004;29: 1193–1208.
[35] Akpinar EK, Akpinar S. Determination of the wind energy potential for Maden, Turkey. Energy Conversion and Management 2004;45(18-19):2901–14.
[36] Ulgen K, Hepbasli A. Determination of Weibull parameters for wind energy analysis of Izmir, Turkey. International Journal of Energy Research 2002;26: 495–506.
[37] Celik AN. On the distributional parameters used in assessment of the suitability of wind speed probability density functions. Energy Conversion and Management 2004;45(11–12):1735–47.
[38] Kose R. An evaluation of wind energy potential as a power generation source in Kütahya, Turkey. Energy Conversion and Management 2004;45(11–12): 1631–1641.
[39] Persaud S, Flynn D, Fox B. Potential for wind generation on the Guyana coastlands. Renewable Energy 1999;18:175–89.

[40] Balouktsis A, Chassapis D, Karapantsios TD. A nomogram method for estimating the energy produced by wind turbine generators. Solar Energy 2002;72:251–9.
[41] Zhou W, Yang H, Fang Z. Wind power potential and characteristic analysis of the Pearl River Delta region, China. Renewable Energy 2006;31:739–53.
[42] Troen Ib, Lundtang Petersen E. European wind atlas. Roskilde, Denmark: Riso National Laboratory; 1989.
[43] Diaf S, Belhamel M, Haddadi M, Louche A. Assessment of wind resource in southern Algeria. Revue des Energies Renouvelables 2007;10(3):321–7.
[44] Justus CG, Mikhail A. Height variation of wind speed and wind distribution statistics. Geophysical Research Letters 1976;3(5):261–4.
[45] Ahmed Shata AS, Hanitsch R. Electricity generation and wind potential assessment at Hurghada, Egypt. Renewable Energy 2008;33:141–8.
[46] 〈http://www.nordex-online.com〉; 2011.
[47] 〈http://www.wind.com.au/products.htm〉; 2011.
[48] 〈http://www.suzlon.com〉; 2011.
[49] 〈http://www.vergnet.com〉; 2011.
[50] 〈http://www.thewindpower.net/turbine_technical_fr〉; 2011.
[51] Ahmed Shata AS, Hanitsch R. Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt. Renewable Energy 2006;31:1183–202.
[52] Bagiorgas HS, Assimakopoulos MN, Theoharopoulos D, Matthopoulos D, Mihalakakou GK. Electricity generation using wind energy conversion systems in the area of Western Greece. Energy Conversion and Management 2007;48(5):1640–55.
[53] Sarkar M, Hussain M. The potential of wind electricity generation in Bangladesh. Renewable Energy 1991;1:855–7.
[54] Rehman S, Halawani TO, Mohandes M. Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia. Renewable Energy 2003;28:573–83.
[55] Türksoy F. Investigation of wind power potential at Bozcaada, Turkey. Renewable Energy 1995;6–8:917–23.
[56] Lysen EH. 2nd ed.Introduction to wind energy, vol. 82. The Netherlands: Consultancy Services Wind Energy Developing Countries (CWD); 1983 p. 261–79.
[57] Sathyajith M. Wind energy fundamentals, resource analysis and economics. Berlin Heidelberg: Springer-Verlag; 2006.
[58] Adaramola MS, Paul SS, Oyedepo SO. Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria. Energy Conversion and Management 2011;52:3363–8.
[59] de Oliveira Wagner Sousa, Fernandes Antonio Jorge. Economic feasibility applied to wind energy projects. International Journal of Emerging Sciences 2011;1(4):659–81 ISSN: 2222-4254©IJES.
[60] Fingersh L, Hand M, Laxson A. Wind turbine design cost and scaling model. U.S. Department of Energy. Colorado: NREL—National Renewable Energy Laboratory; 2006.
[61] Recalde M. Wind power in Argentina: policy instruments and economic feasibility. International Journal of Hydrogen Energy 2010;35:5908–13.
[62] 〈http://iteconcorp.com/ROICalc.html〉; 2012.